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DICAM

INFLUENCE OF UNCERTAINTIES ON ROTATING FLEXIBLE SHAFT SUSPENDED BY 4-AXIS RADIAL ACTIVE MAGNETIC BEARINGS

μ-SYNTHESIS AND LOOP-SHAPING-DESIGN

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Key words: Rigid rotor, radial active magnetic bearing, robust control.

Parole chiave: Rotore rigido, cuscinetti magnetici attivi radiali, controllo robusto.

Abstract. *This paper shows a comparison about dynamic behavior of a rotating shaft when it is suspended by 4-axis radial active magnetic bearing system. The active magnetic suspension is obtained by two different controllers which realize the robust stability and robust performance. The control systems used are* μ-synthesis and loop shaping design procedure. *Each of these controllers is characterized by four input and four output signals and the introduction of uncertainties on displacement gain and current gain is justified by the simple fact that during the time the component which constitutes these gains can be subjected to torn and worn which can lead the entire system to instability phenomena. The inputs are the feedbacks of four displacement components relative to the four axis of radial active magnetic bearing while the outputs are the control current injected in the plant in order to provide the control of position of two section under the monitoring of ideal sensors. An ideal sensor here is meant to be able to capture small displacements and without presence of noise. The advantages of a four input controller is the absence of velocity components which are present in the state vector such that no observer and speed sensors are need to build a feedback. The comparison of the performances is made through the introduction of same weighting function for the two control system. The weighting functions are introduced in order to define the required performances for the position and control signals. The results are produced by simulations tracking of reference and disturbance rejection are tested in order to provide elements useful to implement the goal of this paper. All simulations and results are performed by MATLab.*

Sommario. *Questo lavoro mostra un confronto sul comportamento dinamico di un albero rotante quando è sospeso da un sistema di cuscinetti magnetici attivi radiali. La sospensione magnetica attiva è ottenuto con due diversi controller che realizzano la stabilità robusta e la prestazione robusta. I sistemi di controllo utilizzati sono:* μ-synthesis and loop shaping design procedure. *Ciascuno di questi controller è caratterizzato da quattro ingressi e quattro segnali di uscita; l'introduzione di incertezze sul guadagno di* *spostamento e guadagno di corrente è giustificata dal semplice fatto che, durante il tempo, il componente che costituisce questi vantaggi può essere sottoposto a usura che può portare l'intero sistema a fenomeni di instabilità. Gli ingressi sono le retroazioni delle quattro componenti di spostamento rispetto ai quattro assi del cuscinetto magnetico attivo mentre l'uscita è la corrente di controllo iniettata nell'impianto per fornire il controllo di posizione di due sezioni sotto il monitoraggio di sensori ideali. Un sensore ideale qui è inteso come capace di catturare piccoli spostamenti in assenza di rumore. I vantaggi di un controllore a quattro ingressi è l'assenza di componenti di velocità nel vettore di stato in modo che nessun osservatore e nessun sensore velocità sono necessari per costruire un feedback. Il confronto delle prestazioni è realizzato attraverso l'introduzione della stessa funzione peso per i due sistemi di controllo. Le funzioni peso sono introdotte al fine di definire le prestazioni richieste per la posizione e i segnali di controllo. I risultati sono prodotti da simulazioni tracciamento di riferimento e reiezione ai disturbi testate per fornire elementi utili per raggiungere l'obiettivo di questo lavoro. Tutte le simulazioni e i risultati sono eseguite con MATLAB.*

1 INTRODUCTION

Active Magnetic Bearings (AMBs) are capable of adjusting the force applied to the supported structure (typically a rotor) within a limited amplitude and bandwidth. Equipped with position sensors and a feedback controller, AMBs can imitate the behavior of physical systems such as a spring damper suspension or more complex structures which are able to suspend flexible rotors. Control theory provides numerous tools to design such controllers with the desired properties and performance. However, most of these tools require a plant model and relatively precise knowledge of the AMBs, sensors and the rotor. So called robust controllers tolerate model inaccuracies, torn and worn of the physical component until a certain margin. A stabilizing controller is necessary to establish levitation [1], so that some parameters are necessary such as the current and stiffness gains. In order to get these data a linearized technique is required. In this case the commonly used linearized model for active magnetic bearing systems describes the plant adequately. There is another technique which allows obtaining the stiffness and current gains, for example Loesch et al. [2] proposed a way to acquire rotor parameters and a stabilizing controller by a simple experiment, which still requires knowledge of some bearing parameters. Methods for online tuning of a given, stabilizing controller to meet the required performance have been presented in [3], [4]. The entire start-up configuration and tuning could be automated when combined with this new method.

Obviously there are many control systems which are able to maintain the operating point position of a rotating system such as the integrator of a PID controller [5]; some other control system needs the entire state vector to create the feedback such as the optimal control characterized by a matrix whose number of column is equal to the dimension of state vector. The cutting edge of control systems is represented by μ-synthesis and loop shaping design procedure The reason is not only to recover the operating point position without integrator but also the possibility to avoid the use of some sensors to capture further components belonging to the state vector, a problem that usually is solved by the introduction of observers. Advantages derived by using robust control is the possibility to control the system in presence of dynamic perturbation, lacking of modeled dynamic, neglected nonlinearities, effects of reduced-order models, system-parameter variation due to environmental changes, hysteresis, torn and worn factors. Moreover it is used also in the case of presence of sensor and actuator noise. Due to high surface speed and active control capabilities, radial active magnetic

bearings hold great promise for high speed machining spindles [7]. The control problem posed by this application is examined and the development of an advanced prototype is reviewed. A µ-synthesis framework is proposed for this problem and it is shown that the minimization of the susceptibility to machining chatter may be easily put into this framework. In addition to handling uncertainties in sensor and actuator components, this formulation may also include an uncertainty representing the range of cutting tools for the spindle.
The proposed control algorithms are developed using µ-analysis to obtain robust stability and robust performance in simulation of the investigation. In simulations work, two different active suspension control algorithms are used. A similar approach is applied in [8] where a comparison between different controllers is performed in order to analyze the differences on the dynamic behavior. Many other applications of robust control are performed through loop-shaping design procedure such [9] were an H_∞ controller was performed by evolution optimization to control a robot arm. The loop shaping method is commonly used also to obtain tradeoffs of robust stability and robust performance. This technique is a particular optimization problem to guarantee closed loop stability at all frequencies.

2 MATHEMATICAL MODEL

Particular configuration shown in this work considers a rotor with four degree of freedom with eight poles for each radial active magnetic bearing, having a slope of 45° with regard to horizontal direction so that the force's resultant supports the rotor along the *x* and *y* direction though their resultant. In the flexible configuration the system is studied according to lumped parameters:

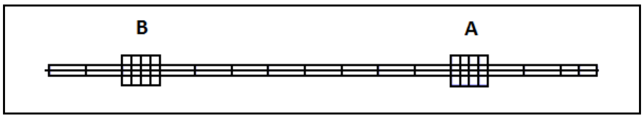

Fig.1:Schematic view of 4-axis rotating shaft supported by two radial radial active magnetic bearings with sensors.

The system is subjected to a state of uncertainty about current and displacement gains respectively $k_{(x,y)(A,B)}$ and $k_{(ix,iy)(A,B)}$ by the parameters $\delta_{k_{(x,y)(A,B)}}$ and $\delta_{k_{(ix,iy)(A,B)}}$ in the range $P_{k_{(x,y)(A,B)}}$ and $P_{k_{(ix,iy)(A,B)}}$. The equations of motion are referred to both plane *x* and *y* and it has the following expression by considering the lumped parameters:

$$\mathbf{M}\ddot{\mathbf{q}}(t)+(\Omega\mathbf{G}+\mathbf{C})\dot{\mathbf{q}}(t)+\mathbf{K}\mathbf{q}(t)=\mathbf{B}_f\mathbf{f}(\mathbf{i}_c(t),\mathbf{q}_b(t)) \tag{1}$$

By introducing a transformation of coordinates in a modal truncation (2) which lead the system to modal coordinates, the system is analyzed according the equation of motion (3):

$$\begin{cases}\mathbf{q}(t)=\mathbf{M}^{-\frac{1}{2}}\mathbf{P}\mathbf{r}(t),\mathbf{M}_r=\mathbf{P}^{\mathbf{T}}\mathbf{M}^{-1/2}\mathbf{M}\mathbf{M}^{-1/2},\mathbf{G}_r=\mathbf{P}^{\mathbf{T}}\mathbf{M}^{-1/2}\mathbf{G}\mathbf{M}^{-1/2}\\ \mathbf{q}_b(t)=\mathbf{C}_M\mathbf{q}(t),\mathbf{K}_r=\mathbf{P}^{\mathbf{T}}\mathbf{M}^{-1/2}\mathbf{K}\mathbf{M}^{-1/2},\mathbf{C}_r=\mathbf{P}^{\mathbf{T}}\mathbf{M}^{-1/2}\mathbf{C}\mathbf{M}^{-1/2}\end{cases} \tag{2}$$

$$\mathbf{M}_r\ddot{\mathbf{r}}(t)+(\Omega\mathbf{G}_r+\mathbf{C}_r)\dot{\mathbf{r}}(t)+\mathbf{K}_r\mathbf{r}(t)=\mathbf{P}^{\mathbf{T}}\mathbf{M}^{-1/2}\mathbf{B}_f\mathbf{f}(\mathbf{i}_c(t),\mathbf{q}_b(t)) \tag{3}$$

or rather the sum of the nominal value and the uncertainties contributes. The introduction of uncertainties on mass, transverse and polar moment of inertia is justified by the simple fact that in many publications usually the uncertainties in displacement gain and in current gain is used. This is not so correct due to the fact that these parameters are carried out by a precise calculation called Taylor's series expansion so there are not uncertainties about this ancient calculation. Since the second principle of mechanic relates the force to the mass and acceleration, it is more justified to introduce the uncertainties on mass, transverse and polar moment of inertia in order to cover the difference between the linear and non linear pattern of force produced by magnets versus control current. This discrepancy is assumed equals to a certain range meant in percentage.

The magnetic force, produced by radial active magnetic bearings, is linearized by Taylor's series expansion which leads to the expression of the force (4), [5],[6]:

$$\mathbf{f}(\mathbf{i}_c(t),\mathbf{q}_b(t)) \approx \mathbf{K}_S\mathbf{q}_b(t)+\mathbf{K}_I\mathbf{i}_c(t) \tag{4}$$

where

$$\begin{cases} k_{(x,y)(A,B)} = k_{(x,y)(A,B)}\left(1+P_{k_{(x,y)(A,B)}}\delta_{k_{(x,y)(A,B)}}\right) = k_{(x,y)(A,B)} + \Delta k_{(x,y)(A,B)} \\ k_{(ix,iy)(A,B)} = \bar{k}_{(ix,iy)(A,B)}\left(1+P_{k_{(ix,iy)(A,B)}}\delta_{k_{(ix,iy)(A,B)}}\right) = \bar{k}_{(ix,iy)(A,B)} + \Delta\bar{k}_{(ix,iy)(A,B)} \end{cases} \tag{5}$$

The last expression leads to the matrix formulation:

$$\begin{aligned} \mathbf{K}_S &= \bar{\mathbf{K}}_S + \bar{\mathbf{K}}_S\mathbf{P}_{K_S}\boldsymbol{\Delta}_{K_S} \\ \mathbf{K}_I &= \bar{\mathbf{K}}_I + \bar{\mathbf{K}}_I\mathbf{P}_{K_I}\boldsymbol{\Delta}_{K_I} \end{aligned} \tag{5a}$$

3 CONTROLLER

In order to provide a stabilizing effect to control the position of the rotor, a suitable control system must be performed because no magnetic levitation can be stabilized without controller [1] [4]. Here two different controllers are performed or rather loop shaping design and μ-synthesis robust control by making the assumption (6) in the mathematical model (7);

$$\begin{cases} \mathbf{x}_1(t)=\left[r_{xA}(t) \quad r_{xB}(t) \quad r_{yA}(t) \quad r_{yB}(t)\right]^{\mathbf{T}}, \mathbf{x}_2(t)=\left[\dot{r}_{xA}(t) \quad \dot{r}_{xB}(t) \quad \dot{r}_{yA}(t) \quad \dot{r}_{yB}(t)\right]^{\mathbf{T}} \\ \mathbf{q}(t)_{sensor} = [\mathbf{C}_{mt} \quad \mathbf{0}]\left[\mathbf{x}_1^{\mathbf{T}}(t) \quad \mathbf{x}_2^{\mathbf{T}}(t)\right]^{\mathbf{T}}, \mathbf{y}_{amp}(t)=\mathbf{i}_c(t) \end{cases} \tag{6}$$

For all kind of robust control systems performed in this paper, a state space equation in a package form is built as in (7). Usually a rotor supported by radial active magnetic bearing needs to reach some desired performances that are described by weighting functions. The weighting functions introduced in the plant are relative to position and control signal performances in order to impose limits in the current value and maximum displacement of each rotor's section. The block schemes are shown in the figure 2 with the introduction of weighting functions;

$$
\begin{cases}
\begin{bmatrix} \dot{\mathbf{x}}_1(t) \\ \dot{\mathbf{x}}_2(t) \\ \dot{\mathbf{x}}_{amp}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} & \mathbf{0} \\ -\mathbf{M}_b^{-1}\mathbf{K}_b + \mathbf{M}_t^{-1}\mathbf{P}^{\mathbf{T}}\left(\sqrt{\mathbf{M}}\right)^{-1}\mathbf{B}_f\bar{\mathbf{K}}_S\mathbf{C}_{mt} & -\Omega\mathbf{M}_b^{-1}\mathbf{G} & \mathbf{M}_b^{-1}\mathbf{P}^{\mathbf{T}}\left(\sqrt{\mathbf{M}}\right)^{-1}\mathbf{B}_f\bar{\mathbf{K}}_I\mathbf{C}_{amp} \\ \mathbf{0} & \mathbf{0} & \mathbf{A}_{amp} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1(t) \\ \mathbf{x}_2(t) \\ \mathbf{x}_{amp}(t) \end{bmatrix} + \\
+\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{M}_b^{-1}\mathbf{P}^{\mathbf{T}}\left(\sqrt{\mathbf{M}}\right)^{-1}\mathbf{B}_f\mathbf{P}_{k_s} & \mathbf{M}_b^{-1}\mathbf{P}^{\mathbf{T}}\left(\sqrt{\mathbf{M}}\right)^{-1}\mathbf{B}_f\mathbf{P}_{k_i} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Delta}_{K_s} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\Delta}_{K_i} \end{bmatrix} \begin{bmatrix} \mathbf{z}_1(t) \\ \mathbf{z}_2(t) \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{B}_{amp}(t) \end{bmatrix} \mathbf{y}(t)_{amp} \\
\begin{bmatrix} \mathbf{z}_1(t) \\ \mathbf{z}_2(t) \end{bmatrix} = \begin{bmatrix} \left(\bar{\mathbf{K}}_S\mathbf{C}_{mt}\right)^{4\times4} & \mathbf{0}^{4\times4} & \mathbf{0}^{4\times8} \\ \mathbf{0}^{4\times4} & \mathbf{0}^{4\times4} & \left(\bar{\mathbf{K}}_I\mathbf{C}_{amp}\right)^{4\times4} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1(t) \\ \mathbf{x}_2(t) \\ \mathbf{x}_{amp}(t) \end{bmatrix} + \begin{bmatrix} \boldsymbol{\Delta}_{K_s} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\Delta}_{K_i} \end{bmatrix} \begin{bmatrix} \mathbf{z}_1(t) \\ \mathbf{z}_2(t) \end{bmatrix} + \mathbf{y}(t)_{amp} \\
\mathbf{y}(t)_{sensor} = \begin{bmatrix} \mathbf{I}^{4\times4} & \mathbf{0}^{4\times4} & \mathbf{0}^{4\times8} \end{bmatrix} \begin{bmatrix} \mathbf{x}_1^{\mathbf{T}}(t) & \mathbf{x}_2^{\mathbf{T}}(t) & \mathbf{x}_{amp}^{\mathbf{T}}(t) \end{bmatrix}
\end{cases} \tag{7}
$$

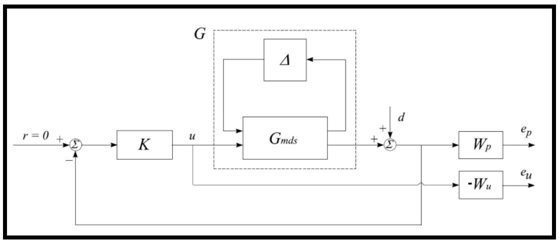

Fig.2:Block schemes of plant with the introduction of weighting functions as further outputs.

where G_{mds} is the nominal plant meant without uncertainties, K is the controller, d the disturbances, e_p and e_u the output of weighting function with regard the position and control signal respectively. The presence of weighting functions produces an increase of state vector's variables so that the new plant is P as shown in figure 3;

All controller used in this paper are characterized by a common concept or rather the robustness. The closed-loop system achieves robust stability if it is internally stable for all possible plant models $G = F\left(G_{mds}, \Delta\right)$. In the present case this means that the system must remain stable for any value of $\delta_{k_{(x,y)(A,B),(ix,iy)(A,B)}}$.

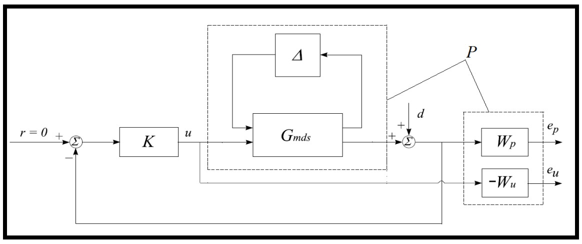

Fig.3:Block schemes of plant showing the new plant.

Since that weighting functions are introduced in order to provide some characteristics on the system's output the robust performance criterion (8) is introduced for all $G = F\left(G_{mds}, \Delta\right)$;

$$
\left\| \begin{bmatrix} W_p\left(I+GK\right)^{-1} \\ W_u K\left(I+GK\right)^{-1} \end{bmatrix} \right\|_\infty < 1 \tag{8}
$$

4 RESULTS, SIMULATIONS AND DISCUSSION

The simulations are performed by considering the data contained in the table I:

Table 1: Data for simulation

Symbol	Description	S.I.
m	mass of rotor	$2.3Kg$
I_P	polar moment of inertia	$8\times10^{-4}\,Kg\cdot m^2$
I_T	transverse moment of inertia	$6\times10^{-2}\,Kg\cdot m^2$
$P_{\bar{k}_{(x,y)(A,B)},\bar{k}_{(ix,iy)(A,B)}}$	uncertainties percentage	10%
$\delta_{\bar{k}_{(x,y)(A,B)},\bar{k}_{(ix,iy)(A,B)}}$	range of uncertainties	$[-1,1]$
$\bar{k}_{(x,y)(A,B)}$	nominal displacement gain	$144000N/m$
$\bar{k}_{(ix,iy)(A,B)}$	nominal current gain	$38N/A$

Another set of data are referred to the transfer function introduced in the plant of our system. Some authors introduce scalar weighting functions in order to describe a certain constant value they want to obtain as a particular output. Figures 4 and 5 show the frequency response of weighting function with regard to the displacement performances in order to analyze the sensitivity function or the disturbances can affect the dynamic response of the system. In the figure 4 is shown the sensitivity function for the loop shaping controller design and we can see that the system has a good attenuation of disturbances until a certain value of frequency equals to 2×10^3 and 3×10^3 rad/s according to controlled axis. In the figure 5, μ-synthesis exhibits an excessive response which goes over the line for the entire range of frequency shown by weighting function which is represented by a continuous line. In the same figure only two of four axis or rather the axes of bearing "A" lay at the limit of the weighting function plot, this means that for the bearing "A" the effect of the disturbances on plant is not attenuated efficiently. Figure 6 and 7 show respectively that robust stability for the μ-synthesis that is not maintained for all values of frequencies and such variable behavior is maintained also for the performances analysis (right figure) in fact, some range of frequencies are characterized by the condition μ<1 while LSDP is able to do taht for a more large range of frequency. According to the figure 8 and 9, the study of disturbances rejection and reference's tracking is performed. It is done for all studied controllers. In the figure 8 and 9 the disturbance rejection and reference's tracking test are performed according a simulation characterized by a range of time of sixty seconds and an injection signal built as a square wave with a period of 20*s* and amplitude of $10^{-6}m$.

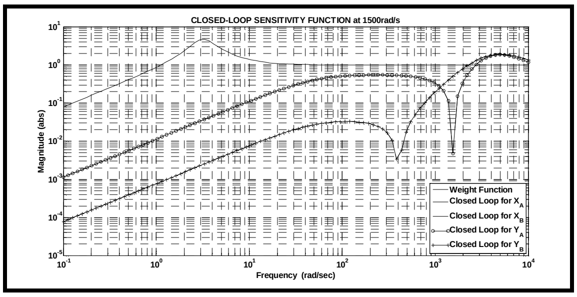

Fig.4:Sensitivity function with LSDP controller.

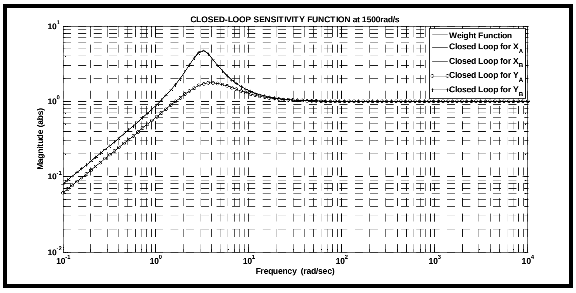

Fig.5:Sensitivity function with μ-synthesis controller.

All implemented controllers are capable to support the requirements to reject the disturbance and follow the reference, but they do it in a different manner according to the controllers. Their dynamic behavior is typical of damped system where a certain overshoot's value is present and different according to the controllers. The loop-shaping controller provides good performance for the disturbance rejection due to the short period to extinct the transient response and small overshoot's value if compared with those offered by µ-Synthesis. In the figure 9 has been shown the reference's tracking simulations. The input signals, to analyze the dynamic behavior of the system, are the same for the disturbance rejection one, but in this case the position of each suspended section must follow the reference input, because the system must be able to adapt itself at every desired condition required by the user. Also in this case µ-Synthesis have the same dynamic behavior and loop-shaping exhibits a more ready response due to the short settling time and small overshoot.

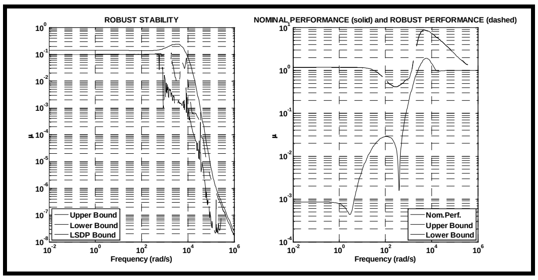

Fig.6: Robust stability, nominal and robust performance with LSDP controller.

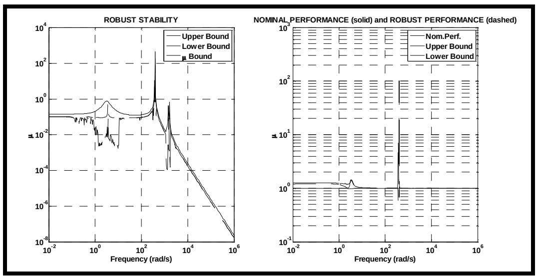

Fig.7: Robust stability, nominal and robust performance with µ-Synthesis

4 CONCLUSIONS

Comparison by two different control systems is built for a suspended rotor with flexible configuration by radial active magnetic bearings. The comparison shows that loop-shaping design procedure provides the best performance to eliminate the disturbances and to follow the reference's signal. This performances in terms of displacement and transient response must be referred to a mathematical results in terms of µ-value, in fact, the presence of weighting function lead both controllers to assume the dynamic behavior shown in the plot. Loop shaping design controller eliminates the transient response more fast than exhibited by µ-Synthesis but both controller are able to reach asymptotic stability to the exogenous excitation such as disturbances and reference's tracking test.

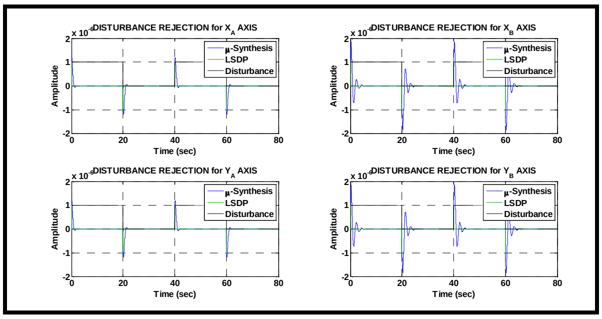

Fig.8: Disturbance rejection test at 1500rad/s.

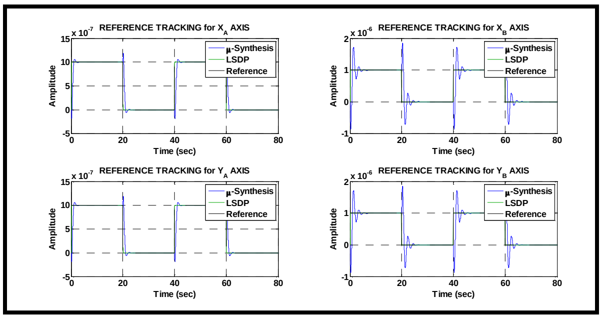

Fig.9: Reference tracking test at 1500 rad/s.

During the transient response loop shaping controller has a short time response and short settling time to reach stable position and it is characterized by only one oscillation while the μ-Synthesis looks like to have less damping effect that leads it to show more oscillations during transient response. In the future development the use of uncertainties will be performed ina stochastc way by the equivalent stochatstic linearization in order to carried out the profermance of the controller correspondin the different procedure of linearization

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